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RESEARCH MEMORANDUM

EXTENDED OPERATION OF TURBOJET ENGINE WITH PENTABORANE

By James W. Useller and William L. Jones

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Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
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SUMMARY

A full-scale turbojet engine was operated with pentaborane fuel continuously for 22 minutes at conditions simulating flight at a Mach number of 0.8 at an altitude of 50,000 feet. This period of operation is approximately three times longer than previously reported operation times.

Although the specific fuel consumption was reduced from 1.3 with JP-4 fuel to 0.98 with pentaborane, a 13.2-percent reduction in net thrust was also encountered. A portion of this thrust loss is potentially recoverable with proper design of the engine components. The boron oxide deposition and erosion processes within the engine approached an equilibrium condition after approximately 22 minutes of operation with pentaborane.

INTRODUCTION

Pentaborane has been considered for use as a turbojet-engine fuel to improve the specific fuel consumption and thus provide an increase in the range of high-speed aircraft. The altitude performance of a full-scale turbojet engine using pentaborane is reported in reference 1. The limited availability of pentaborane restricted the test period of reference 1 to only 6 minutes of continuous operation with pure pentaborane. Although a substantial improvement in specific fuel consumption was reported over that for a hydrocarbon fuel, large quantities of boron oxide were deposited on the engine components and produced a deterioration of the engine thrust and component performance with increasing operation time.

The short duration of the investigation of reference 1 made possible only a limited understanding of the decrease in performance with the deposition of boron oxide on the engine components. It was, however, speculated that the deposition and erosion processes of the oxide in the engine might reach an equilibrium condition. The rate of deposition would then equal the rate of erosion, and the engine performance would remain relatively constant with continued operation.

The investigation reported herein was conducted at the request of the Bureau of Aeronautics, Department of the Navy, to study the rate of engine performance deterioration with boric oxide deposition from the use of pentaborane and to determine whether an equilibrium condition would be reached between the deposition and erosion of the oxide. Sufficient pentaborane was accumulated to permit continuous operation for 22 minutes. The engine was operated in an altitude test chamber of the NACA Lewis laboratory at a Reynolds number index simulating flight at an altitude of 50,000 feet and a Mach number of 0.8. The data presented herein demonstrate the effect of extended operation with pentaborane on 3748
the engine component and over-all performance. Photographs of the oxide deposits on the major engine components are also included.

APPARATUS

Engine

A schematic diagram of the engine used in this investigation is shown in figure 1. The engine consisted of a 12-stage axial-flow compressor, eight tubular combustion chambers, and a single-stage turbine. A variable-area exhaust nozzle permitted operation at the maximum allowable turbine-outlet gas temperature of 1250° F and rated engine rotational speed. The fuel nozzles and the combustor liners were modified. A special fuel nozzle of the air-atomizing type was installed in the upstream end of each combustion chamber. The fuel nozzles contained a passage for JP-4 fuel in addition to that for pentaborane. A schematic diagram of the fuel nozzle is shown in figure 2.

Previous operation of this engine with pentaborane produced high temperatures at the root of the turbine blades. Therefore, the flow area of nine holes in the downstream end of each combustion liner was increased to alter the temperature pattern at the face of the turbine. It was intended that the blade root temperatures would be lowered to values consistent with the standard temperatures as determined by stress limitations of the turbine.

Fuel System

The pentaborane fuel system was pressurized with helium forcing the fuel from a tank through a metering device into the special fuel nozzles in the engine. Provision was made for purging the pentaborane fuel lines following operation with JP-4 fuel and helium to reduce the handling hazards.

Fuel Properties

Pentaborane of approximately 99-percent purity was supplied by the Bureau of Aeronautics for this investigation. The pentaborane properties are as follows:

Molecular weight	63.17
Melting point, °F	-52
Boiling point at 760 mm Hg, °F	136
Lower heat of combustion, Btu/lb	29,127
Specific gravity at 32° F	0.644
Stoichiometric fuel-air ratio	0.0764
Pounds of boron oxide per million Btu	94

Instrumentation

Location of the instrumentation stations and the amount of instrumentation at each station are shown in figure 1. The total-pressure probes at the combustor outlet and in the tailpipe were of the purge type in order to prevent contamination and plugging by the boric oxide. Engine airflow was measured at the engine inlet (station 1). The fuel flow was measured by a rotating-vane flowmeter.

PROCEDURE

The engine operating conditions were established with JP-4 fuel to simulate flight at a Mach number of 0.8 at an altitude of 50,000 feet. After the engine had reached equilibrium conditions, a transition was made in engine fuel from JP-4 to pentaborane. Engine performance data were collected at 30-second intervals. Engine speed and exhaust-gas temperature were maintained nearly constant at rated conditions by varying the fuel flow and exhaust-nozzle area. The duration of operation with pentaborane was 22 minutes.

Following the pentaborane operation, the engine was inspected, and the boron oxide deposits were photographed. After the inspection, the deposits were dissipated by operation with JP-4 fuel.

In order to eliminate the data scatter caused by small deviations in establishing operating conditions of inlet temperature and pressure and exhaust pressure, the data have been adjusted to a condition which corresponds to a simulated altitude of 50,000 feet and a flight Mach number of 0.8. In addition to the minor pressure and temperature adjustments necessary to establish NACA standard altitude conditions, the engine total-temperature ratio was adjusted to a constant value of 3.3 to eliminate deviations in inlet temperature. The engine pressure ratio was also adjusted in accordance with the temperature ratio. The unadjusted data as taken during the investigation are presented in tabular form in table I. Appendix A contains a list of the symbols used herein, and the method of calculation employed is given in appendix B.

RESULTS AND DISCUSSION

Oxide Formation and Deposition

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The combustion of boron compounds results in the formation of boron oxide, which is a viscid fluid at a temperature of 1100° F, solidifies at lower temperatures, and vaporizes at much higher temperatures. During the 22 minutes of operation of this investigation, approximately 300 pounds of pentaborane were consumed by the engine, and about 830 pounds of boron oxide were formed. The major portion of the oxide was carried off in a liquid state by the gas stream, but significant amounts were condensed and deposited on the relatively cool metal surfaces of the engine.

Examination of the engine fuel nozzles revealed that deposits had formed on the tips of some of the nozzles. The photograph in figure 3 shows the type of formation encountered. These deposits were relatively hard and appeared to be a mixture of boron and boron oxide. Because the location of deposits altered the fuel spray pattern emitting from the nozzle, it is believed that the fuel was able to strike the walls of the combustor liner and thereby increase the severity of deposition in the combustor.

The deposits collected in the engine during this investigation were relatively light (fig. 4). Figure 4(a) shows the comparatively severe deposits that were formed when the fuel nozzle accumulated deposits, while figure 4(b) exhibits a relatively clean combustion chamber. Although the oxide deposition in the engine combustor may be a function of several factors, small-scale tests (ref. 2) demonstrated that the predominant one is the spraying of the fuel on the combustor-liner walls.

The deposits encountered on the engine spark plugs are shown in figure 4(c). These deposits presented no obstacle to subsequent reignition of the engine. The deposits that collected on the combustor-turbine transition section and on the turbine rotor are shown in figures 4(d) and (e), respectively.

The major portion of the deposited oxide was found in the engine tailpipe downstream of the turbine (fig. 4(f)). The tendency of the deposited boron oxide to flow like a highly viscid fluid may be seen in the formations in the tailpipe. The deposits also formed on the exhaust nozzle (fig. 4(g)) and tended to flow downstream from the engine with the gas stream.

The distorted fuel-spray pattern caused by the deposits on the fuel nozzles, in addition to increasing the deposit formation in the combustor and disturbing the airflow through the combustor, shifted the fuel distribution and caused a distorted fuel-air pattern and a resulting shift in the combustor-outlet temperature profile. This shift in temperature profile had an effect on the turbine-inlet temperature profile. Figure 5 shows the local temperature profiles measured at the turbine inlet downstream of two combustors. The fuel nozzle of combustor A was coated with the oxide deposit shown in figure 3.

Effect of Deposits on Component Performance

The accumulation of boron oxide deposits on the surfaces of the engine affects the performance of the components of the engine, but fortunately appreciable quantities of the deposits are eroded by the gas stream through the engine. The net result of erosion and deposition on the component performance is shown in figures 6 to 9.

The combustion efficiency and average combustor total-pressure loss (fig. 6) did not significantly deviate from those obtained during operation with JP-4 fuel, nor did they vary during prolonged operation with pentaborane. The pressure drop through the turbine increased, as may be seen from the increasing turbine pressure ratio of figure 7. After about 14 minutes the pressure ratio reached an equilibrium condition and leveled off. The turbine efficiency (fig. 7) exhibited a gradual decrease from 83 percent with JP-4 fuel to a minimum of 79 percent after 22 minutes of operation with pentaborane.

In an effort to understand qualitatively the effect of the oxide on turbine operation, a motion picture was made of the turbine wheel through a window in the tailpipe during operation with pentaborane. The presence of the oxide in the gas stream tended to obscure the individual frames of the movie, so that only an artist's sketch based on the movie is shown herein. The sketch of figure 8 indicates the condition observed downstream of the turbine. The molten oxide is believed to flow along the walls of the primary combustor and through the turbine passages near the outer wall. Although the boron oxide is initially dispersed throughout the gas stream, the relatively cooler surfaces of the walls promote deposition of the oxide in this region. The high viscosity of the molten oxide causes it to adhere in spherical form along the walls during flow.

The variation of the tailpipe total-pressure losses during the use of pentaborane is shown in figure 9. The increase of these losses with time is similar to the trend shown for the turbine performance in figure 7. The tailpipe total-pressure loss with initial pentaborane operation is about 7 percent, approximately 2 percent higher than during operation with JP-4 fuel. The immediate rise in tailpipe total-pressure loss is attributed to the immediate changes in the turbine-outlet, and consequently the tailpipe, Mach number effected by the change in thermodynamic properties and mass flow of the exhaust gas when pentaborane is introduced.

The tailpipe total-pressure loss reached a maximum of 12 percent after 20 minutes of operation with pentaborane, although the rate of increase was relatively small after about 14 minutes. This continued change in tailpipe pressure loss is also the result of changes in the tailpipe Mach number. During operation with pentaborane the tailpipe Mach number is increased because of the decreased performance of the turbine, as previously discussed. The decreased turbine performance necessitated adjustment of the exhaust-nozzle area to maintain a constant turbine-outlet temperature. Another small increase in the tailpipe total-pressure loss also resulted from the increased coefficient of friction of the wall due to accumulated deposits during operation with pentaborane. The combination of these effects on the tailpipe Mach number is reflected as the tailpipe total-pressure loss shown in figure 9. 3748

Effect on Over-All Performance

The decrease in turbine and tailpipe performance with accumulation of boron oxide may be expected to be reflected by a similar change in the over-all performance of the engine. Figure 10 shows the decrease in engine total-pressure ratio with extended use of pentaborane. The engine total-temperature ratio was held constant at a value of 3.3. Equilibrium was never quite reached, since the pressure ratio continued to decrease, although at a decreasing rate, even after 20 minutes of operation.

The net thrust of the engine as calculated from the exhaust-pressure and weight-flow measurements is shown in figure 11. An initial decrement in thrust of about 6.2 percent occurred with pentaborane. With prolonged use of pentaborane, the net thrust continued to decrease as deposits accumulated in the engine. After about 12 minutes, the rate of deterioration of the thrust was less and an equilibrium condition was approached.

The reasons for the thrust loss indicated in figure 11 are shown in detail in figure 12. They include: (1) The higher heating value of pentaborane results in a lower fuel-flow rate for a given heat release. This is reflected as a reduction in mass flow through the turbine and tailpipe. The reduced mass flow requires an increase in turbine pressure ratio. (2) The change in thermodynamic gas properties due to the pentaborane fuel also results in an increase in turbine pressure ratio. The combination of these effects causes a lowering of turbine-outlet pressure. The lower turbine-outlet pressure and reduced mass flow cause an initial thrust loss of about 3.5 percent (fig. 12). An additional thrust loss of 2.7 percent results from the effects of the reduced turbine-outlet pressure on the tailpipe pressure loss. Thus the initial total thrust loss with pentaborane fuel was about 6.2 percent.

With continued operation on pentaborane fuel the reduction of turbine efficiency caused further reduction of turbine-outlet pressure with an accompanying increase in tailpipe pressure losses. After 20 minutes of operation the total thrust loss increased to about 13.2 percent.

A portion of this 13.2 percent thrust decrement is potentially recoverable through engine component design. For instance, about 7 percent of the thrust decrement might be recovered by the use of a turbine that would result in a smaller reduction in turbine-outlet pressure with continued pentaborane use. The initial thrust loss due to thermodynamic change in gas properties and change in mass flow at 1 minute in figure 12, however, is not recoverable. The use of an engine that operated with a low turbine-outlet Mach number and the incorporation of a tailpipe designed to have a minimum variation of total-pressure loss for the range of tailpipe Mach number encountered with pentaborane use would reduce the thrust decrement attributed to tailpipe pressure loss in figure 12.

The specific fuel consumption (fig. 13) was reduced from 1.3 pounds per hour per pound of net thrust with JP-4 fuel to about 0.93 with pentaborane. The specific fuel consumption increased somewhat during extended operation with pentaborane and reflects the decrease in thrust shown in figure 11. A maximum value of 0.98 was reached after about 14 minutes of operation.

SUMMARY OF RESULTS

A turbojet engine was operated for 22 minutes (three times longer than previously reported) using pentaborane as the engine fuel. Although the specific fuel consumption was reduced from 1.3 with JP-4 fuel to 0.98 with pentaborane, a 13.2-percent reduction in net thrust was also encountered. A portion of this thrust loss is potentially recoverable with proper design of the engine components.

The reduced rate of engine performance change after 22 minutes of operation indicates that an equilibrium was approached between the deposition and erosion of the boron oxide within the engine, although the performance losses of some of the engine components, such as the turbine, did not increase significantly after about 12 to 14 minutes of operation.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, March 19, 1956

APPENDIX A

SYMBOLS

The following symbols are used in this report:

A	area, sq ft
F_j	jet thrust, lb
F_n	net thrust, lb
g	acceleration due to gravity, ft/sec^2
P	total pressure, lb/sq ft
p	static pressure, lb/sq ft
R	universal gas constant
T	total temperature, $^{\circ}$R
V	velocity, ft/sec
w_a	airflow, lb/sec
w_f	fuel flow, lb/hr
w_g	gas flow, lb/sec
γ	ratio of specific heats
δ_a	ratio of engine-inlet total pressure to total pressure at Mach number of 0.8 and altitude of 50,000 ft
η	efficiency
θ	ratio of engine-inlet total temperature to total temperature at Mach number of 0.8 and altitude of 50,000 ft

Subscripts:

a	air
ac	actual

b	combustor
i	ideal
t	turbine
0	free stream
1	engine inlet
3	compressor outlet
4	turbine inlet
5	turbine outlet
9	exhaust-nozzle inlet

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APPENDIX B

METHOD OF CALCULATION

Engine—Airflow

The compressor-inlet airflow was determined from measurements of the total and static pressure and temperature at the engine inlet (station 1). 3748
Air leakage from the compressor and air supplied to the fuel nozzles, turbine, and special instrumentation were included in the calculation of the accumulated airflow.

Combustion Efficiency

The combustion efficiency of the engine combustor operating with pentaborane was defined as

$$\eta_b = \frac{(T_9 - T_1)_{ac}}{(T_9 - T_1)_i}$$

where T_1 was adjusted to account for the temperature of the air bled and added to the engine at the various locations. The ideal temperature rise was derived from unpublished data.

Turbine Efficiency

The turbine efficiency was calculated from

$$\eta_t = \frac{1 - \frac{T_5}{T_4}}{\left[1 - \left(\frac{P_5}{P_4}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

The ratio of specific heats γ was computed as an average value across the turbine for the gas with the boron oxide present.

It should be recognized that the definition of turbine efficiency involves the equation of state ($pV = RT$) and thus assumes that the fluid under consideration behaves as a perfect gas. The data of reference 3 indicate that upon formation during the combustion of boron compounds the boron oxide particle may be a size that would permit Brownian movement and thus allow the oxide particles to act as a perfect gas. This condition has been assumed to exist in the engine, although some error may be introduced because of the larger particles that enter the stream from the oxide that is accumulated on the engine surfaces. The number of large particles entering the gas stream is considered negligible.

Thrust

The jet thrust was calculated from measurements of the weight flow and tailpipe pressure using the following equation:

$$F_j = \frac{w_{g,9}}{g} V_9 + A_9(p_9 - p_0)$$

The net thrust was calculated by subtracting the adjusted inlet momentum from the jet thrust. When test conditions deviated from the desired simulated flight conditions (flight Mach number, 0.8; altitude, 50,000 ft), the data were adjusted by appropriate values of θ_a and δ_a. Adjustments were made in the thrust when the engine temperature ratio deviated from 3.3.

REFERENCES

1. Useller, James W., Kaufman, Warner B., and Jones, William L.: Altitude Performance of a Full-Scale Turbojet Engine Using Pentaborane Fuels. NACA RM E54K09, 1954.

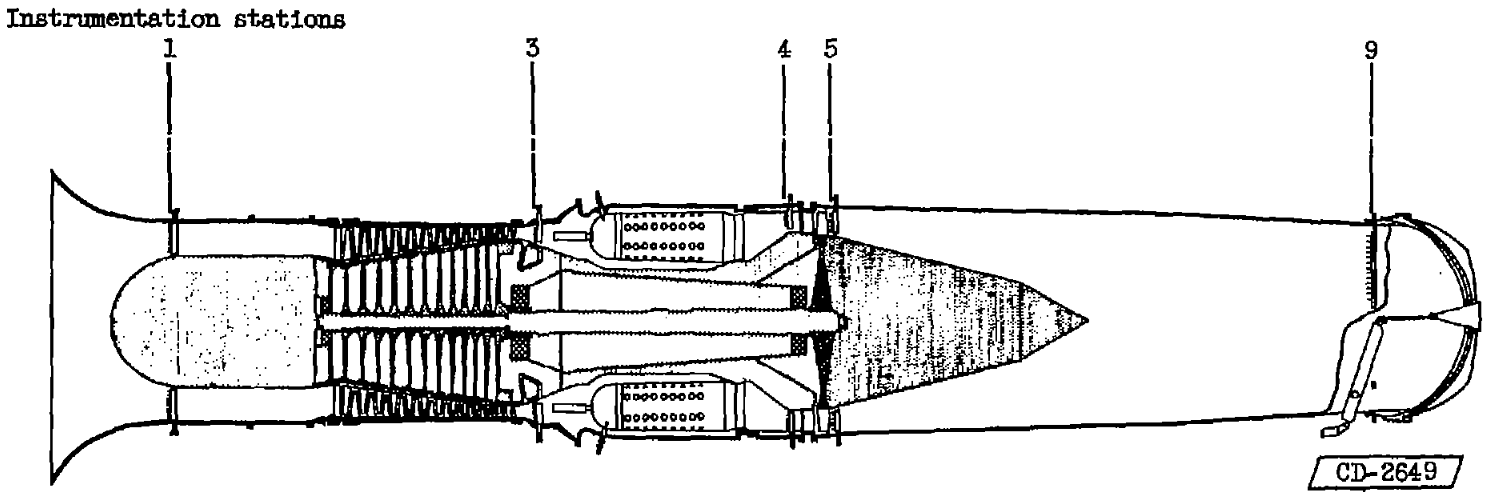
2. Kaufman, Warner B., Branstetter, J. Robert, and Lord, Albert M.: Experimental Investigation of Deposition by Boron-Containing Fuels in Turbojet Combustor. NACA RM E55L07, 1955.

3. Setze, Paul C.: A Study of Liquid Boron Oxide Particle Growth Rates in a Gas Stream from a Simulated Jet Engine Combustor. NACA RM E55I20a, 1955.

TABLE I. - UNCORRECTED ENGINE PERFORMANCE DATA FOR OPERATION WITH PENTABORANE

Operation time, min	Altitude ambient pressure, p_0, lb/sq ft abs	Engine-inlet total pressure, P_1, lb/sq ft abs	Engine-inlet total temperature, T_1, °R	Compressor-outlet total pressure, P_3, lb/sq ft abs	Compressor-outlet total temperature, T_3, °R	Turbine-inlet total pressure, P_4, lb/sq ft abs	Turbine-outlet total pressure, P_5, lb/sq ft abs	Exhaust-nozzle-inlet total pressure, P_9, lb/sq ft abs	Exhaust-nozzle-inlet total temperature, T_9, °R	Engine speed, rpm	Engine-inlet airflow, $w_{a,1}$, lb/sec	Compressor-outlet airflow, $w_{a,3}$, lb/sec	Exhaust-nozzle-inlet gas flow, $w_{g,9}$, lb/sec	Engine fuel flow, w_f, lb/hr
(a)	228	418	517	2293	937	2180	810	768	1699	7950	19.61	19.21	20.20	1274
(a)	234	422	520	2261	938	2148	807	767	1698	7952	19.70	19.31	20.30	1272
(a)	234	423	520	2258	939	2146	810	770	1700	7952	19.67	19.28	20.27	1268
(a)	235	422	520	2254	940	2140	808	764	1700	7946	19.69	19.30	20.30	1265
(a)	231	423	522	2252	941	2138	802	762	1714	7957	19.58	19.17	20.18	1256
0.9	237	429	520	2249	925	2134	811	755	1728	7786	19.64	19.24	19.46	857
1.4	235	425	518	2272	951	2164	794	732	1725	7883	19.78	19.38	19.61	853
2.1	234	422	517	2262	950	2147	789	721	1718	7910	19.87	19.28	19.51	844
2.7	234	423	518	2262	934	2142	778	701	1715	7946	19.83	19.43	19.66	841
3.3	238	422	520	2268	940	2151	776	700	1713	7963	19.78	19.38	19.61	843
4.0	242	425	521	2233	938	2115	782	687	1690	7875	19.67	19.28	19.52	801
4.7	239	422	522	2274	941	2157	770	694	1707	7959	19.63	19.23	19.45	848
5.0	241	421	521	2254	938	2137	782	687	1699	7899	19.58	19.18	19.43	818
5.7	241	421	521	2267	941	2150	769	694	1718	7937	19.63	19.23	19.48	839
6.3	240	422	521	2279	940	2162	761	687	1717	7930	19.76	19.36	19.60	835
6.9	237	421	521	2277	941	2180	760	684	1718	7950	19.62	19.22	19.46	833
7.5	234	421	521	2277	941	2163	755	677	1708	7950	19.69	19.30	19.54	828
8.0	234	421	521	2260	941	2161	746	664	1700	7981	19.64	19.25	19.50	823
8.7	234	421	520	2260	940	2141	741	660	1707	7935	19.68	19.29	19.53	813
9.5	231	418	520	2279	941	2161	750	669	1703	7957	19.61	19.22	19.48	830
10.1	231	424	521	2266	944	2148	743	662	1705	7946	19.78	19.36	19.60	827
10.6	234	421	520	2270	940	2164	748	665	1706	7928	19.64	19.26	19.49	851
11.2	234	422	521	2265	942	2147	743	660	1705	7919	19.73	19.34	19.57	851
11.7	234	422	521	2282	941	2163	744	661	1706	7984	19.70	19.29	19.52	841
12.2	231	422	521	2290	943	2172	743	660	1703	7957	19.73	19.33	19.55	840
12.9	231	421	520	2270	944	2160	743	658	1718	7978	19.69	19.30	19.53	836
13.5	234	417	520	2258	943	2143	739	657	1700	7930	19.46	19.07	19.32	811
14.0	235	421	520	2289	941	2177	748	658	1702	7948	19.60	19.21	19.46	819
14.6	227	421	520	2241	943	2124	724	640	1686	7889	19.56	19.17	19.42	772
15.3	238	421	520	2300	942	2184	737	650	1688	7928	19.62	19.22	19.44	847
15.8	231	424	520	2249	941	2147	730	641	1687	7919	19.69	19.30	19.55	808
16.4	234	421	521	2294	945	2178	745	654	1708	7965	19.68	19.28	19.51	850
16.8	235	421	520	2277	941	2158	738	647	1698	7986	19.67	19.27	19.51	815
17.3	235	421	520	2268	939	2148	732	644	1690	7908	19.65	19.25	19.49	813
17.8	234	421	520	2291	945	2171	737	651	1712	8000	19.72	19.31	19.54	855
18.4	233	417	520	2293	942	2172	739	650	1704	7946	19.59	19.18	19.42	832
18.8	235	421	520	2288	942	2167	736	646	1704	7930	19.68	19.27	19.51	828
19.6	235	418	521	2301	942	2180	755	668	1712	7967	19.63	19.22	19.45	843
20.2	234	417	522	2293	949	2172	760	654	1702	7986	19.58	19.18	19.42	822
20.8	230	417	521	2283	941	2160	740	644	1685	7928	19.62	19.21	19.45	819
21.4	231	417	521	2261	936	2139	727	637	1675	7884	19.46	19.06	19.31	808

[a]JP-4 fuel.



	Station	Static-pressure taps	Total-pressure probes	Total-temperature probes
Engine inlet	1	8	24	12
Compressor outlet	3	2	12	12
Turbine inlet	4	-	20	56
Turbine outlet	5	-	20	5
Exhaust-nozzle inlet	9	-	24	24

Figure 1. - Schematic sketch of turbojet-engine installation.

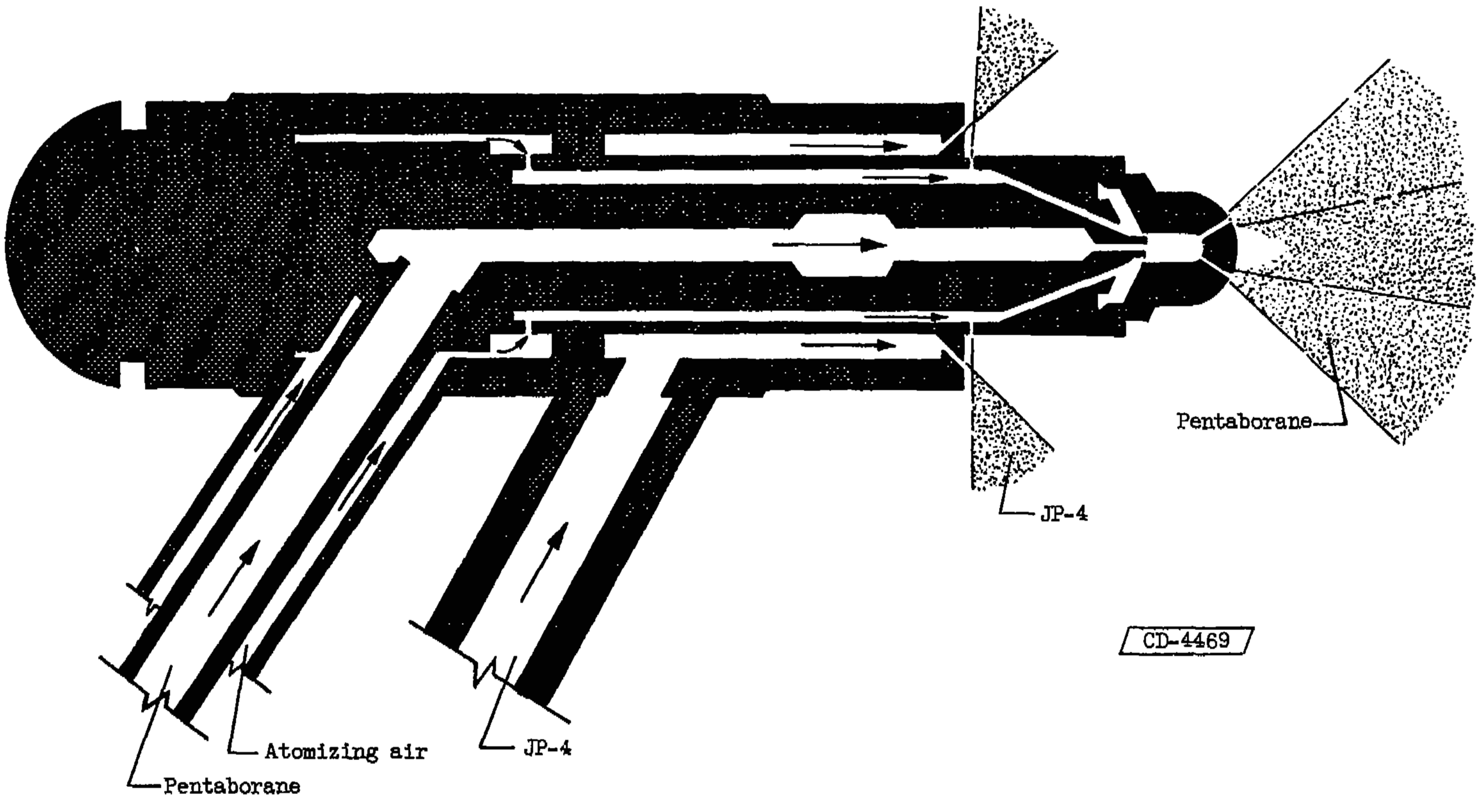


Figure 2. - Air-atomizing fuel nozzle used during pentaborane fuel test in full-scale turbojet engine. Nozzle also provided for use of JP-4 fuel.

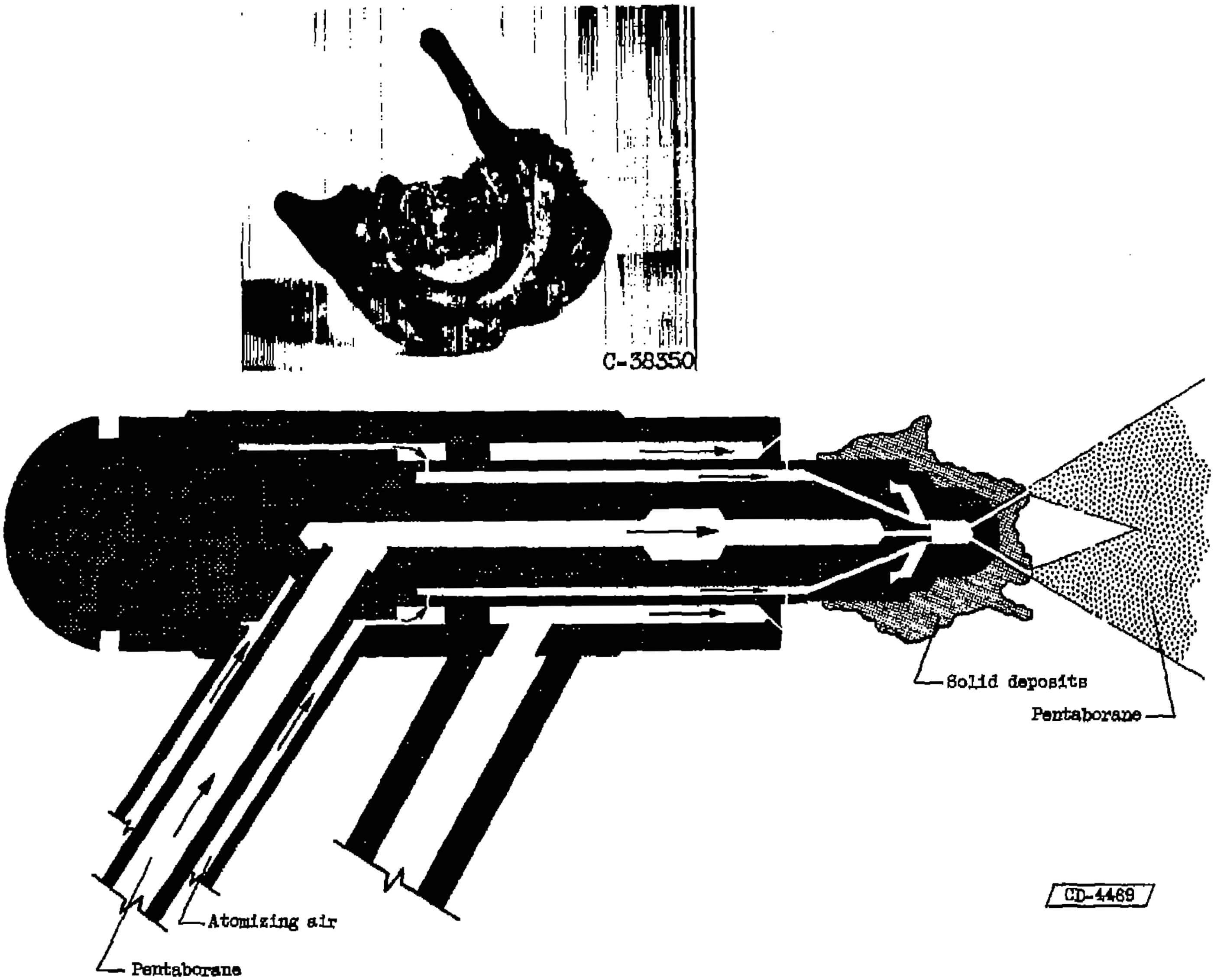


Figure 3. - Boron oxide deposits on turbojet-engine fuel nozzle after 22 minutes of operation with pentaborane.

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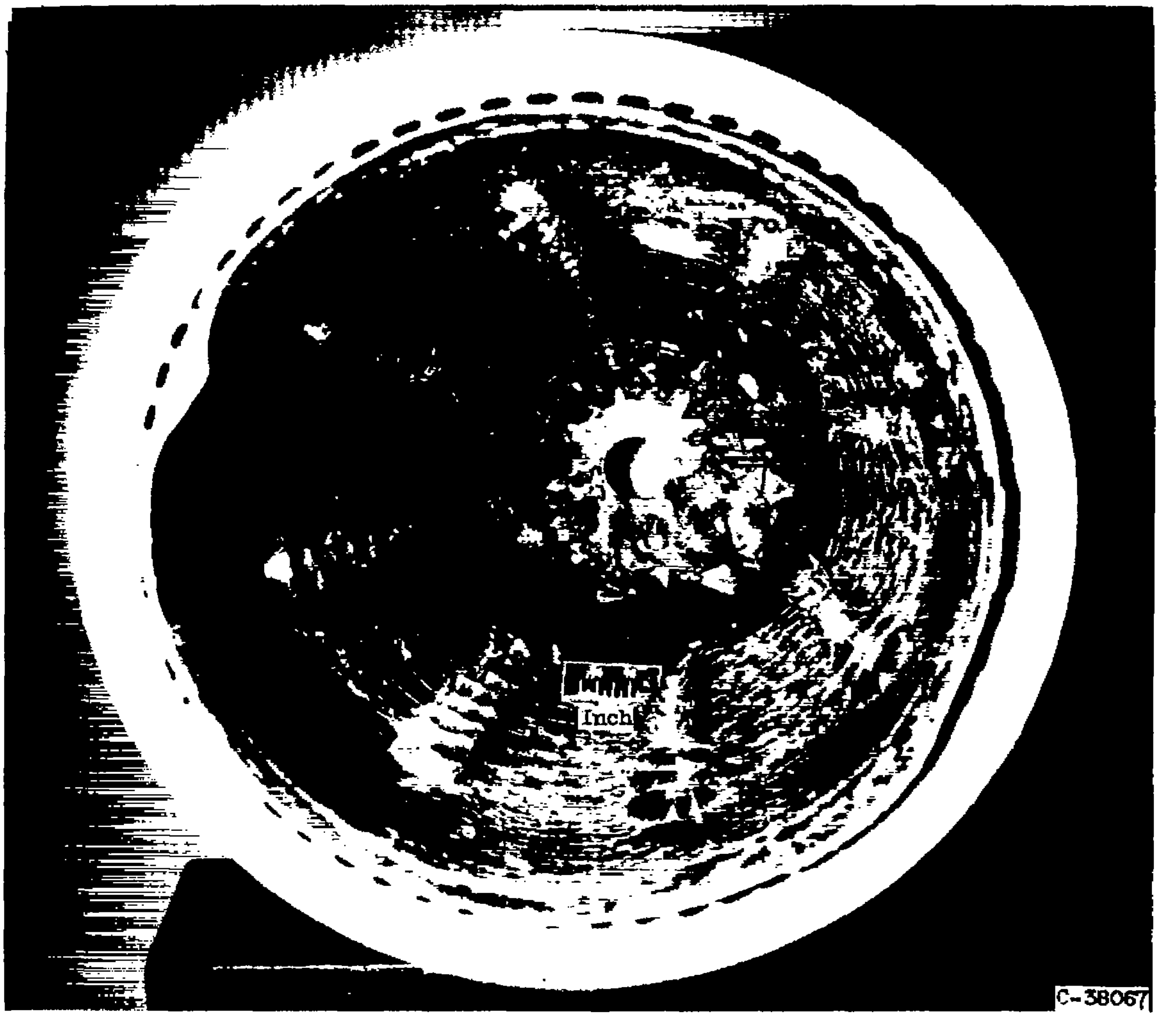
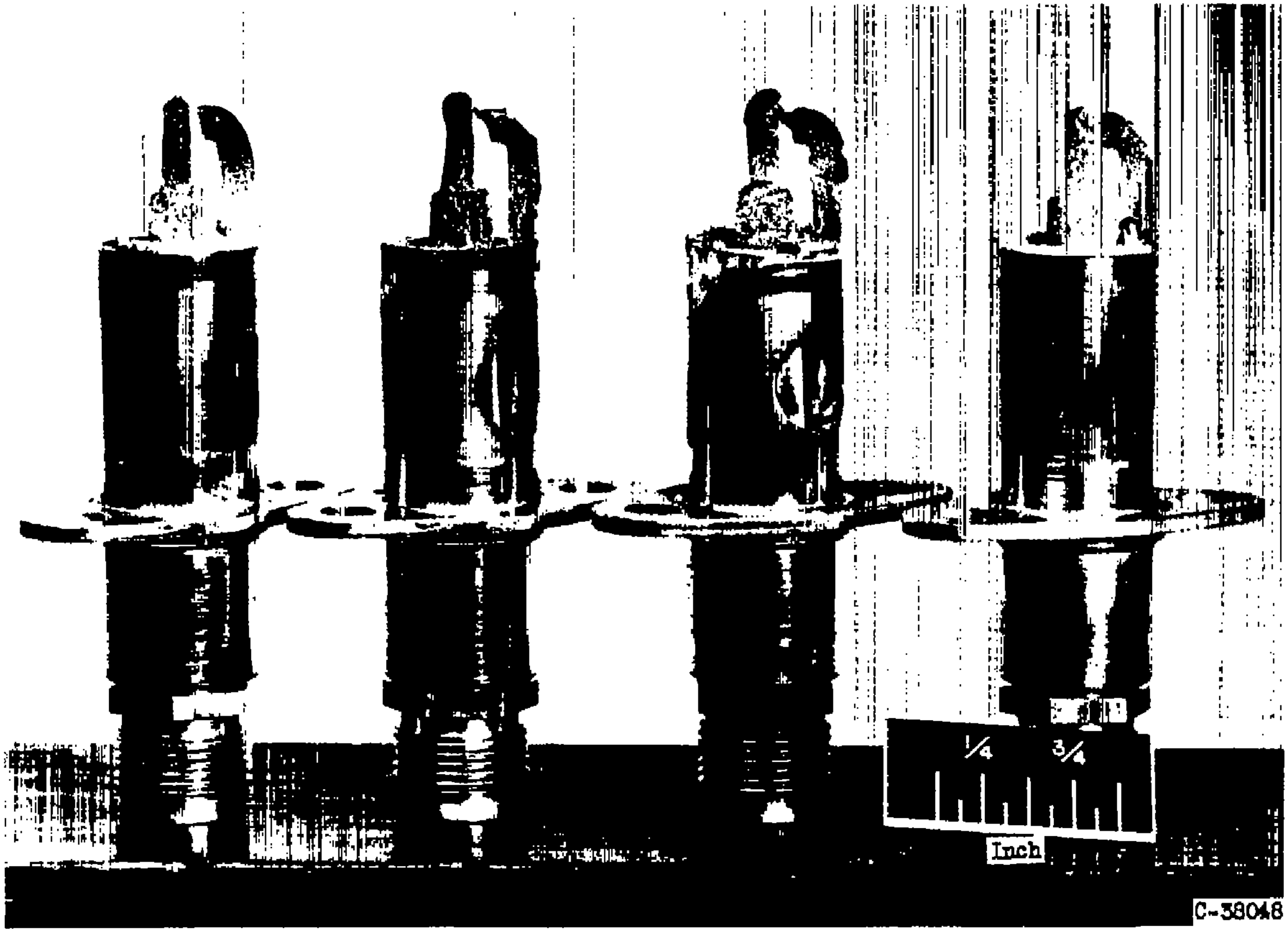


(a) Combustion chamber with greater deposits.

Figure 4. - Boron oxide deposits on turbojet-engine components after 22 minutes of operation with pentaborane.

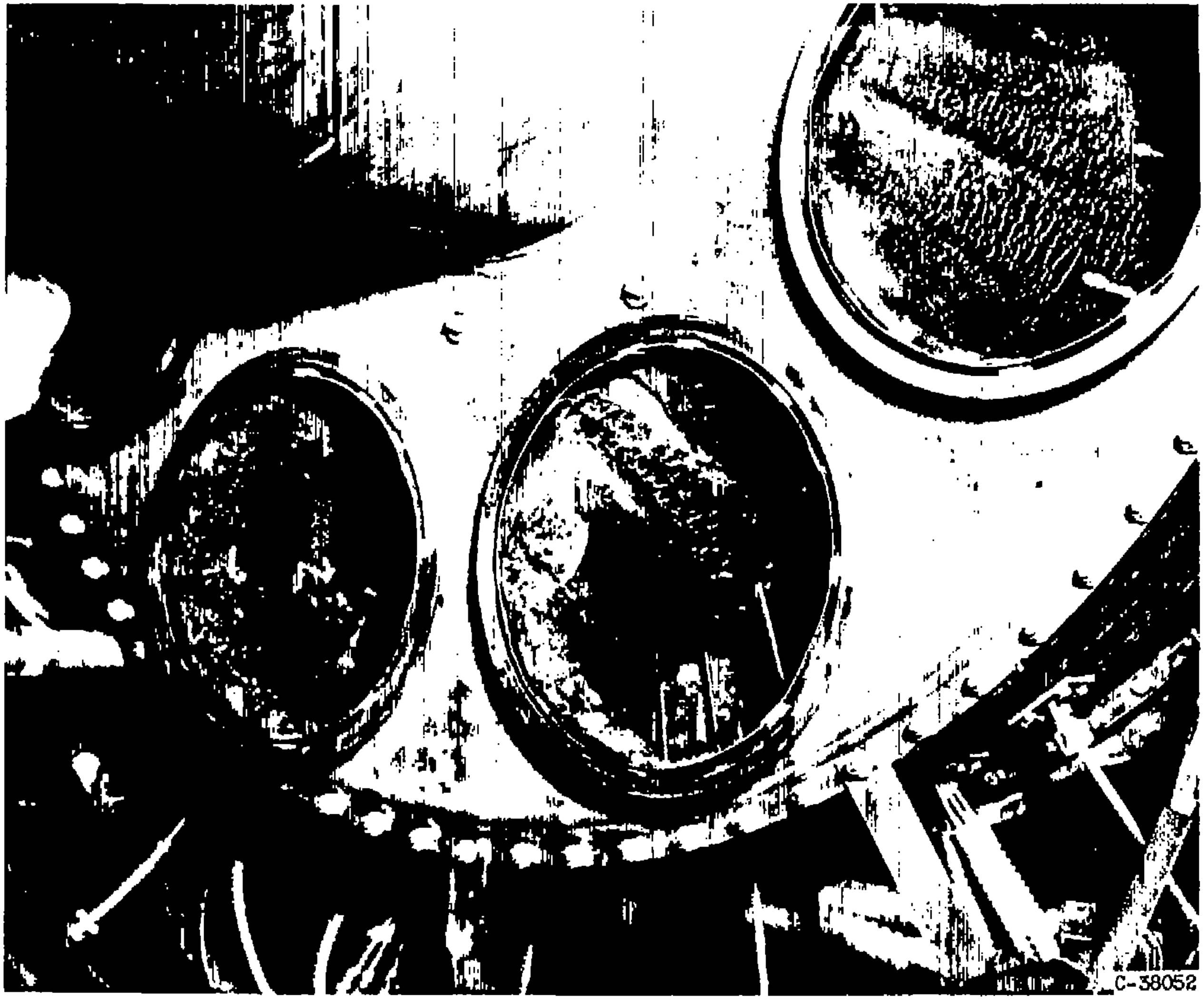
(b) Relatively clean combustion chamber.

Figure 4. - Continued. Boron oxide deposits on turbojet-engine components after 22 minutes of operation with pentaborane.



(c) Engine spark plugs.

Figure 4. - Continued. Boron oxide deposits on turbojet-engine components after 22 minutes of operation with pentaborane.



(d) Combustor-turbine transition section.

Figure 4. - Continued. Boron oxide deposits on turbojet-engine components after 22 minutes of operation with pentaborane.

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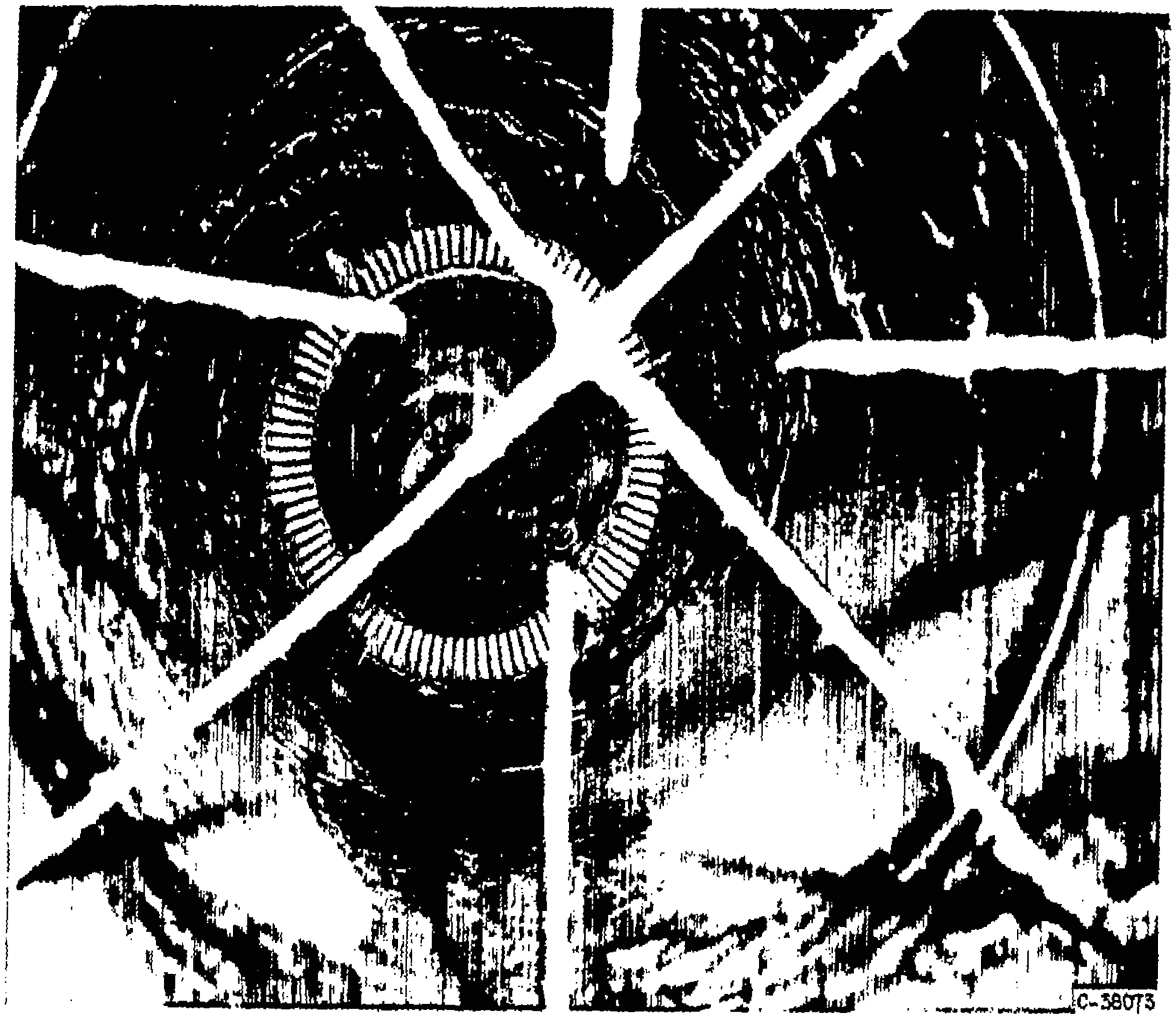
(e) Turbine rotor.

Figure 4. - Continued. Boron oxide deposits on turbojet-engine components after 22 minutes of operation with pentaborane.

[redacted]

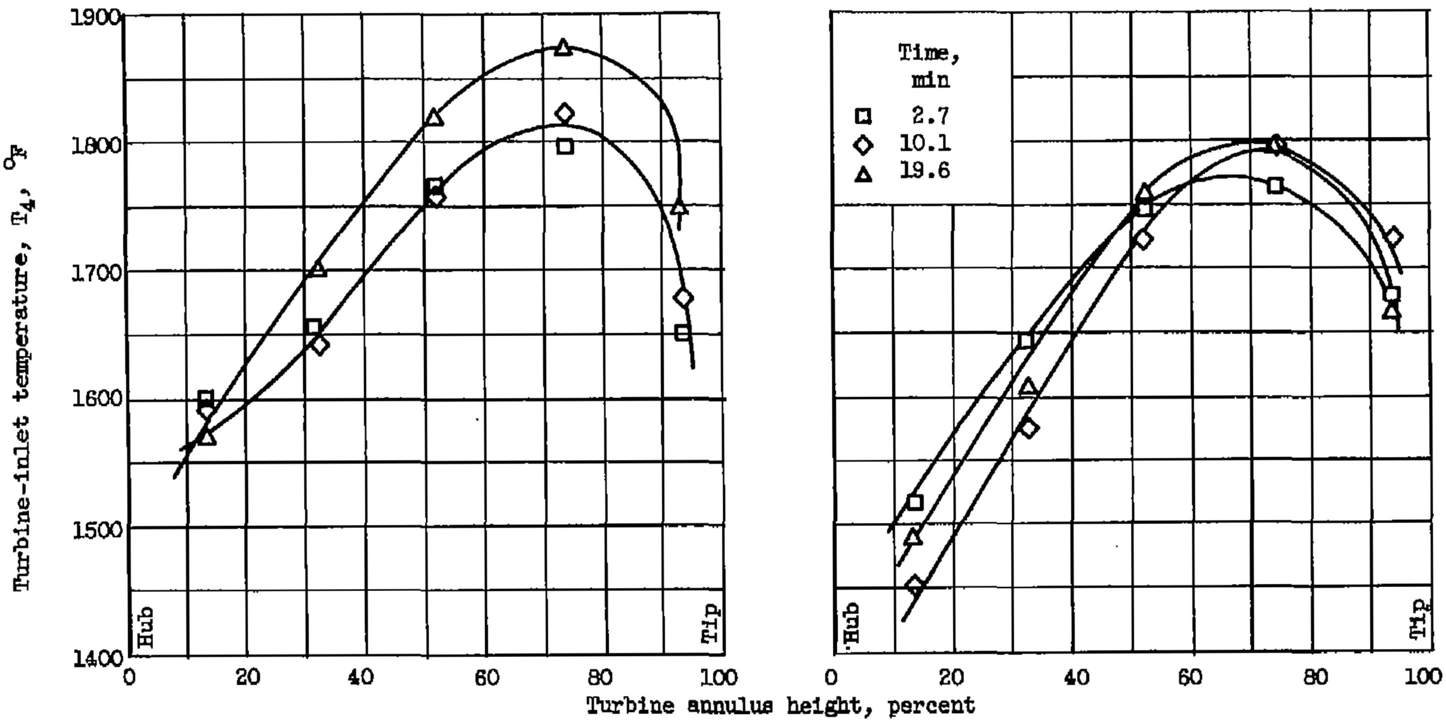


(f) Tailpipe (looking upstream).

Figure 4. - Continued. Boron oxide deposits on turbojet-engine components after 22 minutes of operation with pentaborane.

(g) Exhaust nozzle.

Figure 4. - Concluded. Boron oxide deposits on turbojet-engine components after 22 minutes of operation with pentaborane.



(a) Combustor A. (b) Combustor B.

Figure 5. - Effect of operation with pentaborane fuel on gas temperatures at turbine inlet. Turbojet-engine operation at simulated altitude of 50,000 feet; flight Mach number, 0.8; average turbine-inlet gas temperature, 1620° F.

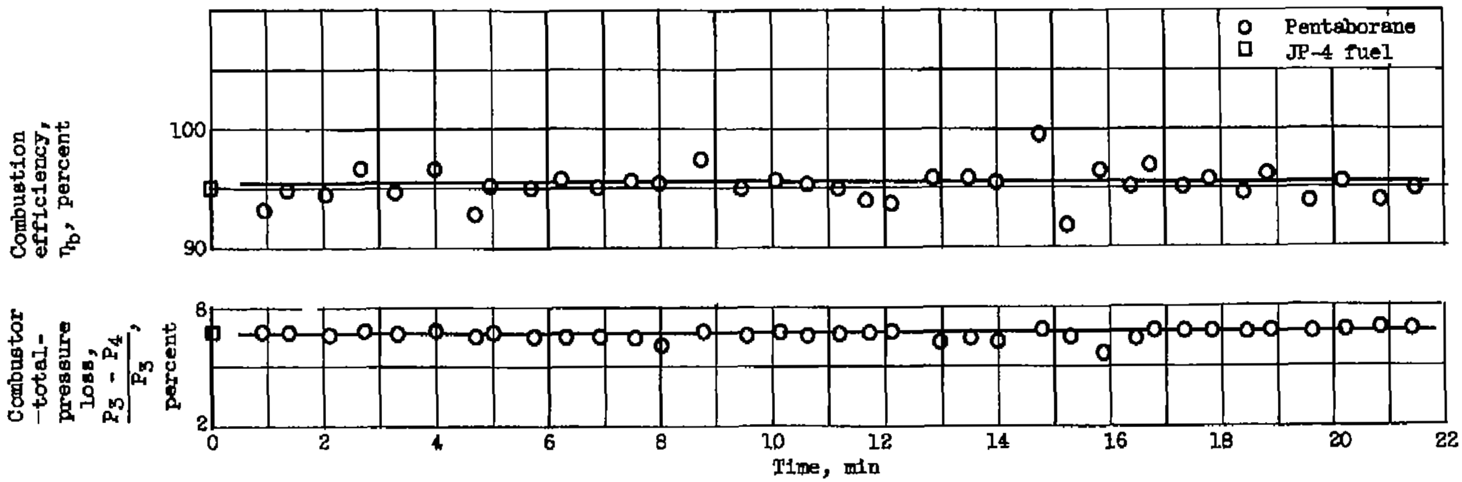


Figure 6. - Effect of operation with pentaborane fuel on combustor performance. Altitude, 50,000 feet; flight Mach number, 0.8.

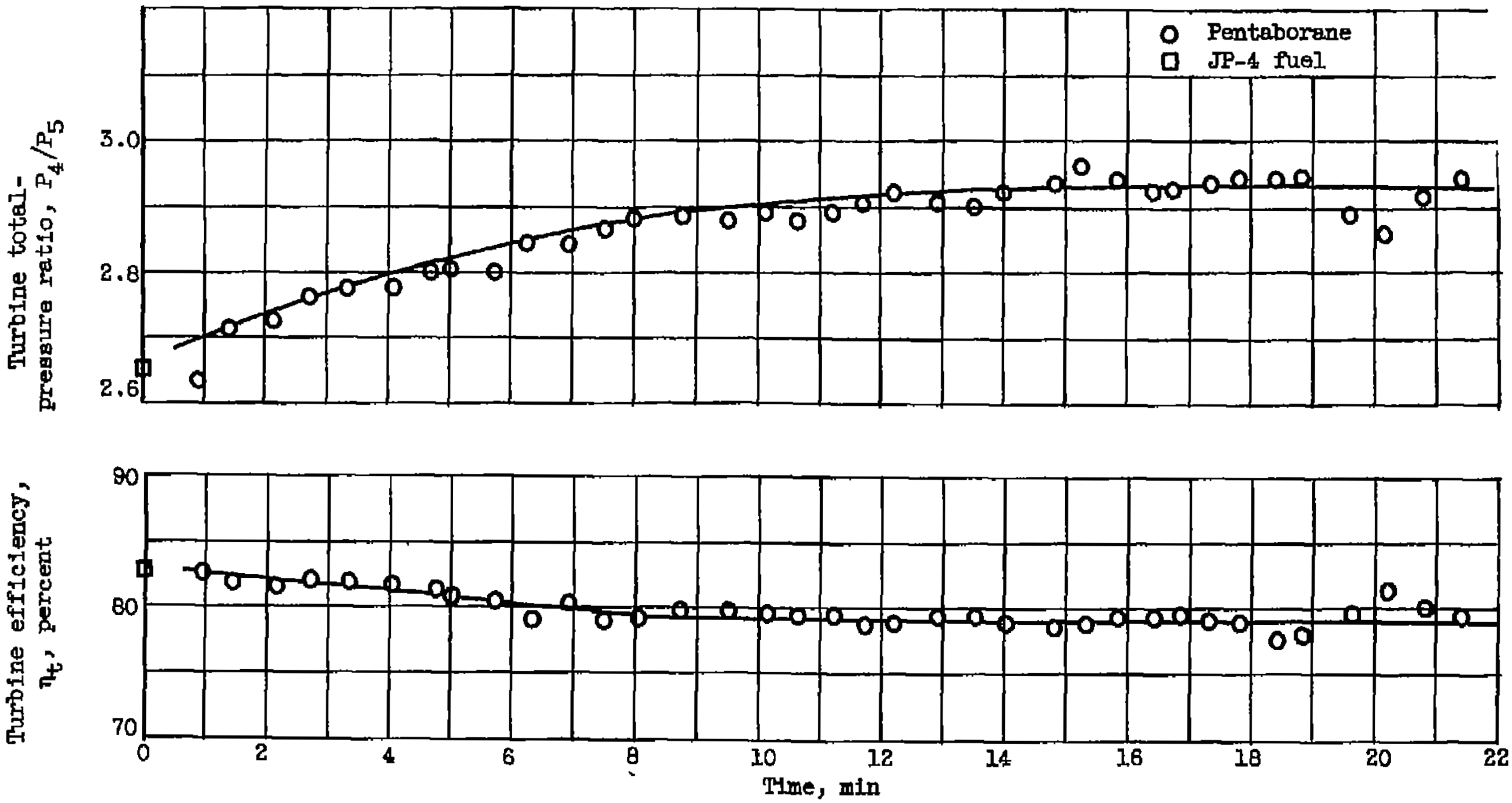


Figure 7. - Effect of operation with pentaborane fuel on turbine performance. Altitude, 50,000 feet; flight Mach number, 0.8.

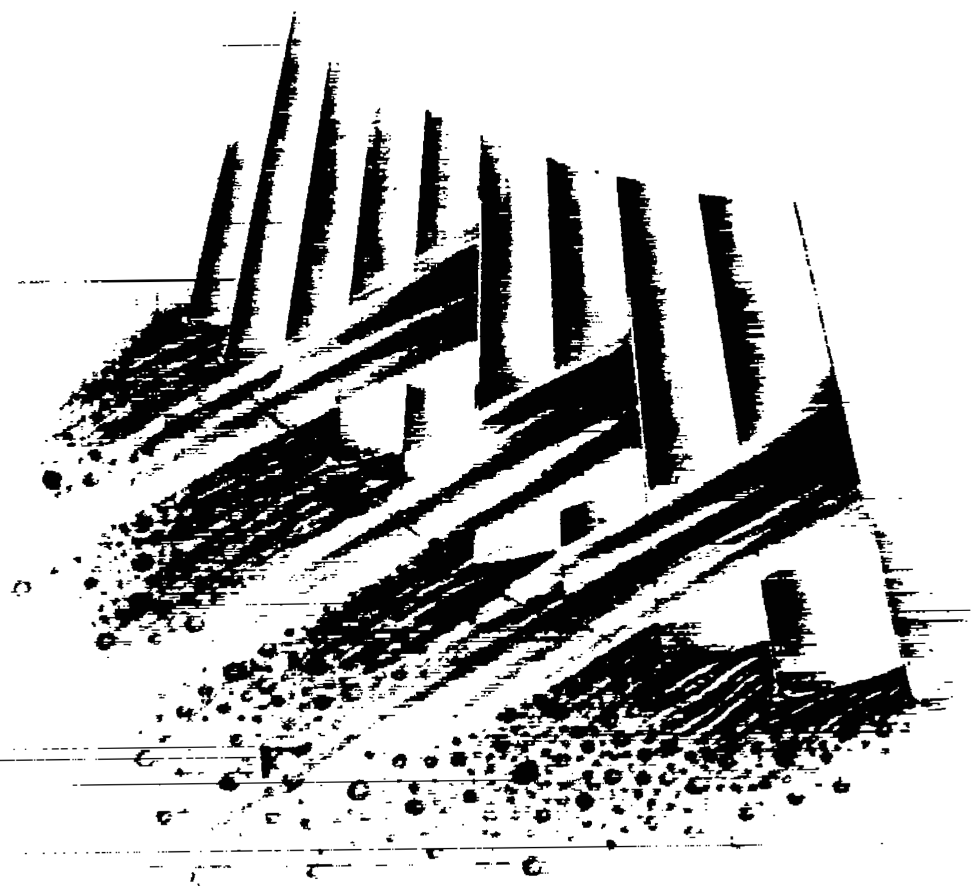


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Figure 8. - Boron oxide flowing through turbine rotor section into turbojet-engine tailpipe.

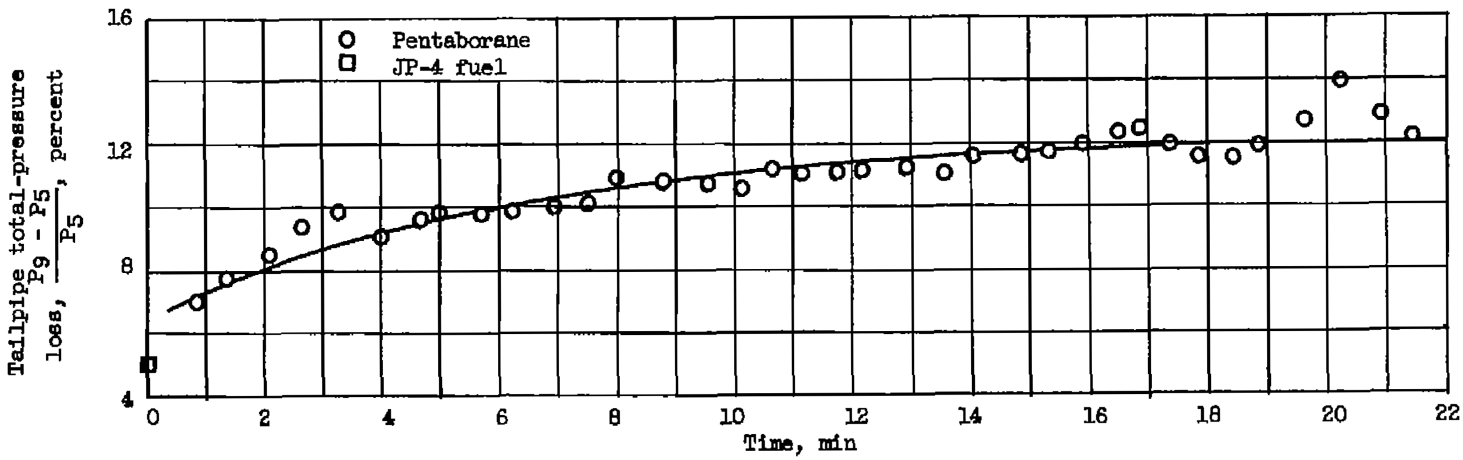

Figure 9. - Variation of tailpipe total-pressure loss with extended operation with pentaborane fuel. Altitude, 50,000 feet; flight Mach number, 0.8.

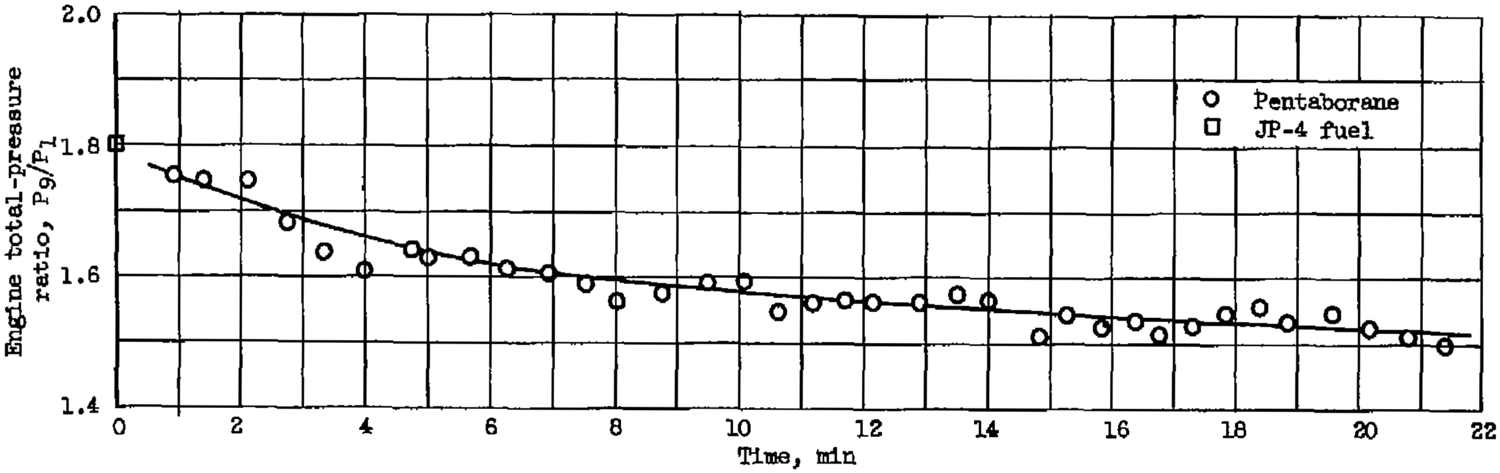

Figure 10. - Effect of operation with pentaborane fuel on engine total-pressure ratio. Altitude, 50,000 feet; flight Mach number, 0.8; engine total-temperature ratio, 3.3.

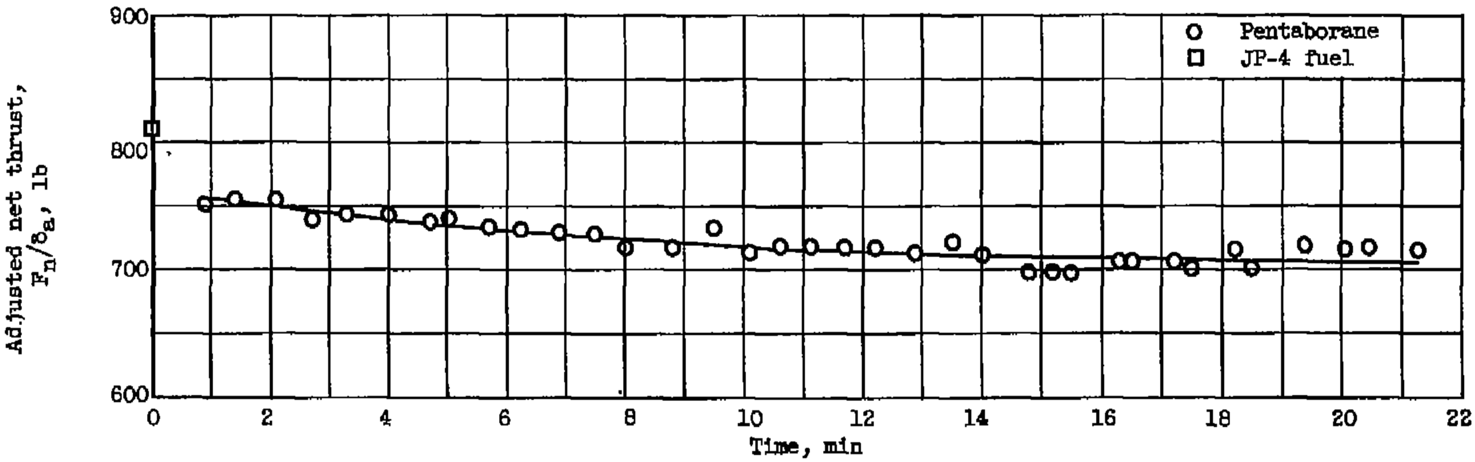

Figure 11. - Effect of operation with pentaborane fuel on net thrust. Altitude, 50,000 feet; flight Mach number, 0.8.

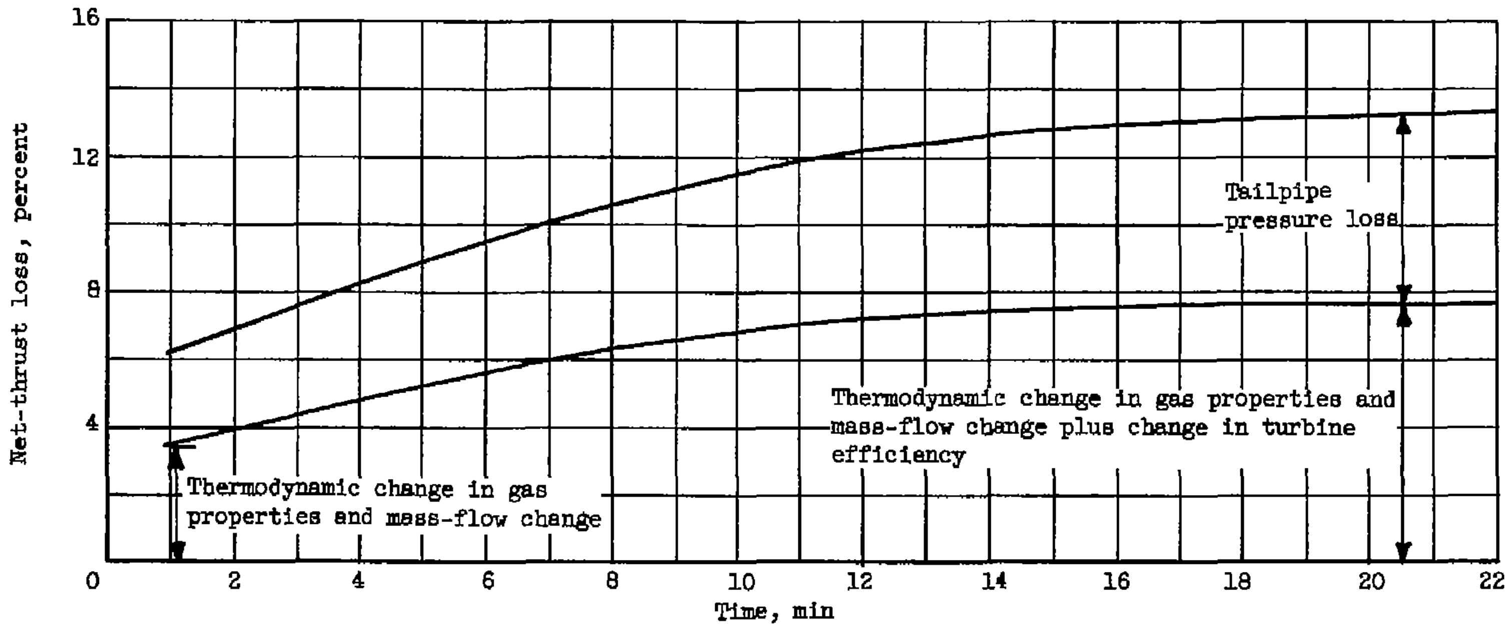

Figure 12. - Net-thrust loss encountered with use of pentaborane fuel. Altitude, 50,000 feet; flight Mach number, 0.8.

[redacted]

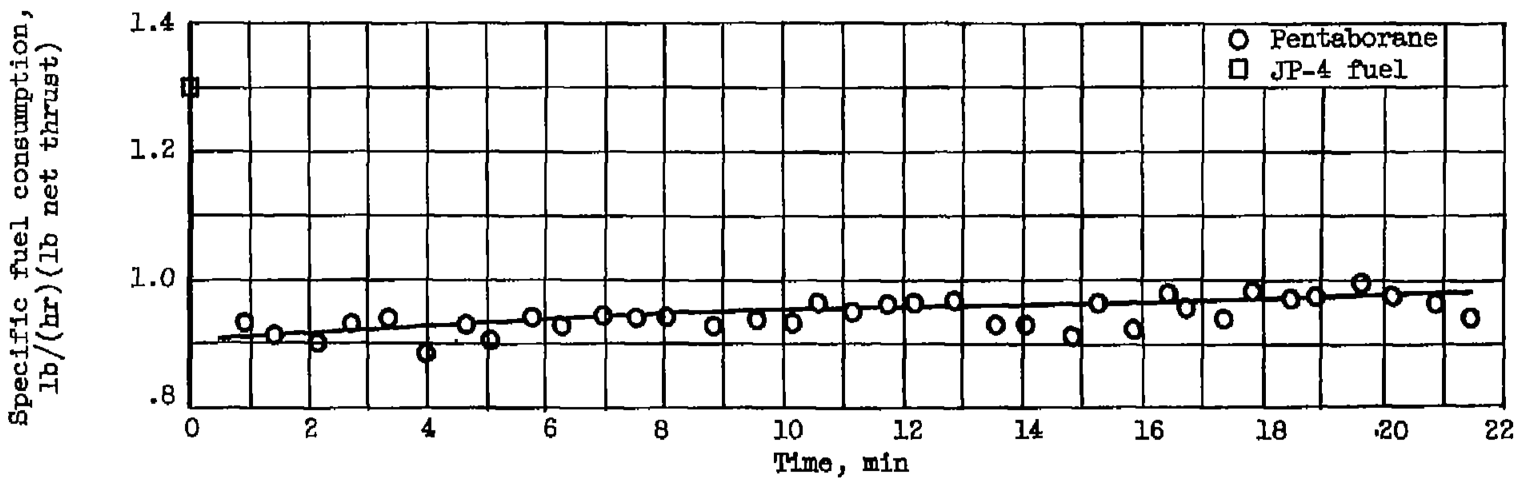

Figure 13. - Effect of operation with pentaborane fuel on specific fuel consumption. Altitude, 50,000 feet; flight Mach number, 0.8.

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